



# Evaluation of the roles of metals and humic fractions in the podzolization of soils from the Amazon region using two analytical spectroscopy techniques

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## ABSTRACT

Soil organic matter (SOM) plays an important role in environmental sustainability, since it is involved in carbon and nutrient cycling. Consequently, it is a key factor to consider in studies concerning global climate change and agronomy. Among the main components of SOM are humic substances (HS), which are divided, according to their solubility, into humic acid (HA), fulvic acid (FA), and humin (HU) fractions. Study of the chemical properties of this organic matter is important for understanding the biogeochemical processes occurring in the soil. The aim of this work was to determine the metals iron (Fe) and aluminum (Al), using flame atomic absorption spectrometry (FAAS) and laser-induced breakdown spectroscopy (LIBS), in order to elucidate the role of organic matter in the transport of these metals in Amazonian soils. The results showed that FA was important for Al, while the HA fraction was more selective towards Fe. The translocations of these metals to deeper profiles in two different soils involved either young and less humified organic matter, or older organic matter with a low degree of humification. Therefore, these two humic fractions were involved in the process of soil podzolization, with FA having a predominant role in the transport of Al, while HA was mainly responsible for the transport of Fe.

## 1. Introduction

Soils play crucial roles in most of the processes that occur on the planet, due to their participation in the main biogeochemical cycles [1]. These involve pedogenetic processes transforming rocks and sediments, whose characteristics are influenced by combinations of soil formation factors such as the source material, climate, microorganisms, and time [2]. In the Amazon, Spodosols develop over time from clay soil or sedimentary formations. Organometallic iron (Fe) and aluminum (Al) oxides present in horizons A and E are transported to deeper soil layers, where they accumulate and give rise to horizons rich in organic matter and organometallic species [2,3].

Soil Organic Matter (SOM) plays a key role in environmental sustainability, since it is related to carbon and nutrient cycling, and is a crucial factor to consider in studies in the fields of global climate change and agronomy. SOM is not homogeneous, and its studies designed to assess the structural and molecular characteristics of organic matter are important, particularly in the Amazon, one of the world's

most important carbon reservoirs [3]. Humic substances (HS) are among the main components of SOM and can be classified, according to their solubility, into humic acid (HA), fulvic acid (FA), and humin (HU) fractions [4]. So, the distribution of the composition of the SOM is a deposit of valuable information about the main processes that occur in the soil. Thus, studies aiming to understand the role, dynamics, interactions and processes that occur in soil organic matter, as well as its humic fractions, are fundamental for the evaluation of soil quality and stability soil in resisting changes over time [3,4].

Determination of the chemical properties of the organic matter, as well as its interaction with metallic species, is essential for understanding the main processes that occur in the soil. The techniques that have been described for this purpose include flame atomic absorption spectrometry (FAAS) and, more recently, laser-induced breakdown spectroscopy (LIBS). The latter is an attractive technique due to its high sensitivity and precision, as well as the requirement for only minimal sample preparation, making it attractive for use in applications that comply with the concepts of Green Chemistry [5]. LIBS is a

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type of atomic emission spectrometry that uses laser pulse as an energy source to vaporize the sample and excite the emission generated from its atoms/ions and/or molecules [6]. The main advantages of LIBS are the potential for simultaneous multi-element analysis becoming an alternative method for the quantification of contaminants, macro/micronutrients, and carbon (C) in soils [7–9]. It has been used in investigations of texture, pH, and macro- and micronutrients in fertilizers and soil organominerals [10–12]. Although LIBS has been used for soil analysis, it has not previously been employed to investigate the humic fractions present in the soil, since multielement analyzes are important in Brazilian soils. Particularly, the Amazon region, is a region of great ecological importance and difficult to access, there is a need for new portability initiatives, such as LIBS, to analyze their soils. The study of the humic fractions in these soils is important to understand the process of formation, stability and accumulation of carbon in these soils, since the carbon model stored in these Amazonian Spodosols has been shown to be more susceptible to decomposition [13]. The conservation of these soils becomes fundamental to avoid high flows of carbon emission by exposing deep profiles or to changing the rainfall regime, imposing prolonged periods of drought and increasing soil microbiological activity, and consequently CO<sub>2</sub> emission. In addition, the study of humic fractions can be reproducible to other natural soils.

The fact of the LIBS technique has been used for analysis of humic fractions is important for the understanding of the dynamics and role of organic matter in Amazonian soil. The aim of this study was to use the FAAS and LIBS techniques to quantify the metals Fe and Al in Amazonian Spodosols. The metals were quantified in whole soil samples and in the different humic fractions (HA, FA, and HU), in order to understand the role of the SOM in the transport of these metals during the podzolization process.

## 2. Materials and methods

### 2.1. Study area

The soil samples (two Spodosols, denoted P1 and P4, shown in Fig. 1) were obtained from a site located in the north of the municipality of Barcelos, near the Demeni River (0°15'18"N; 62°46'36"W) in the middle watershed of the Negro River region in the Amazon plains of Brazil. The regional geology is characterized by sediments of the Içá formation. Sample P1 was from a permanently waterlogged podzol covered by herbaceous meadow of scrubs and grass, locally known as “campina”. Sample P4 was from a well-drained podzol under rainforest vegetation, with no influence of groundwater [13].

### 2.2. Preparation of the samples for analysis

The procedures adopted for sampling, preservation, and preparation of the soils followed the recommendations of official methods [14–16]. Extraction and purification of the humic acid (HA), fulvic acid (FA), and humin (HU) fractions followed the procedures recommended by the International Humic Substances Society (IHSS) [17]. Briefly, the HA and FA were extracted with 0.1 M HCl (Synth) at a soil:extractant ratio of 1:200 (volume in L:mass in g). After centrifugation, the HA fraction was separated from the supernatant (FA) by precipitation at about pH 2.0 with 6 M HCl. The HAs were then suspended in a solution of 0.1 M HCl/0.3 M HF to remove dissolved mineral impurities. After centrifugation, the HA were dialysed at pH 8 (cellulose membrane dialysis tubing, 43 mm, cut-off of 14,000 Da, Sigma-Aldrich). All acidic supernatant containing FA was purified using a proton-saturated cation exchange resin (Amberlite IR-120, Fluka) and DAX-8 resin (Supelite DAX-8, Supelco). The humin (HU) was treated and purified with successive

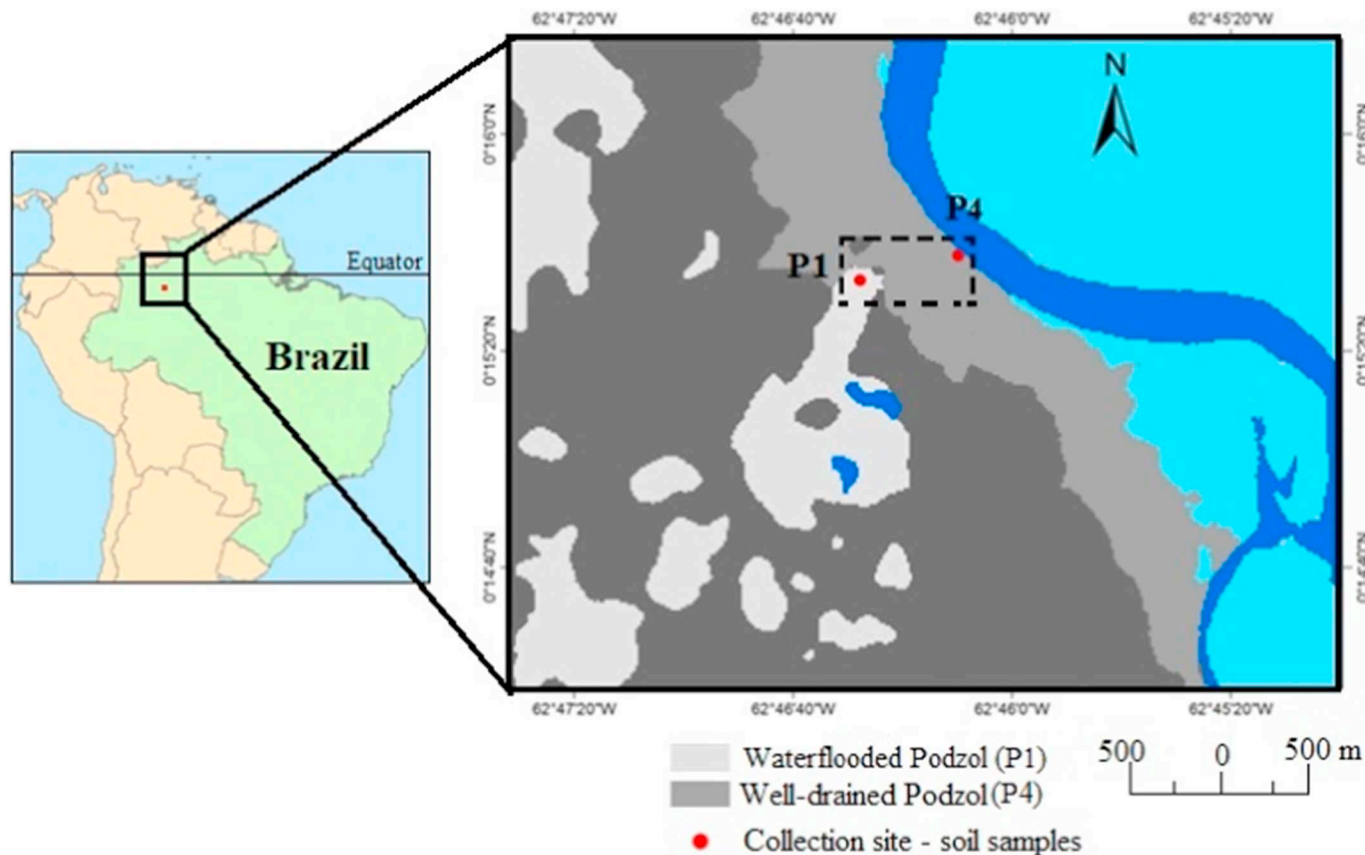


Fig. 1. Map of the sampling sites by soils in the Amazon region. (Adaptation from Tadini et al. [13]).

acid/base washing until the supernatant was colorless. Subsequently, this fraction was washed with deionized water until pH 7.0 and negative for  $\text{AgNO}_3$ , as used by Rice and MacCarthy [18]. The purified HA, FA and HU were lyophilised for the analysis.

### 2.3. Elemental analysis

For the chemical analysis of the carbon composition, 3 mg sample of Humic or Fulvic acid and 10 mg sample of humin or whole soil were weighed in tin capsules using the analytical balance; they were analysed by combustion at 1000 °C using an elemental analyser (Perkin Elmer model 2400). This procedure was performed in duplicate.

### 2.4. Flame atomic absorption spectrometry (FAAS)

Sample decomposition was performed using 100 mg portions of the soils and the humic fractions (HA, FA, and HU), following the recommendations of the United States Environmental Protection Agency (Method 3052) [19]. For this, 100 mg of sample and 9 mL of  $\text{HNO}_3$  concentrate were transferred to glass digester tubes block and heated at 180 °C for 2 h. Subsequently, added by 3 mL of concentrated HCl plus 2 mL of 30% m/m  $\text{H}_2\text{O}_2$ . Tubes were heated at 180 °C for 2 h. The final solution was filtered in 0.2 mm and the volumes completed by deionized water in the 25 mL volumetric flask. Quantification of Fe and Al was performed using a PerkinElmer PinAAcle 900 T flame atomic absorption spectrometer. Calibration curves were constructed using metal standard solutions and a blank (deionized water) prepared in  $1.0 \text{ mol}^{-1}$  HCl (comparable to the sample preparation).

### 2.5. Laser-induced breakdown spectroscopy (LIBS)

The LIBS system employed a Nd:YAG laser operating at 532 nm in the visible (VIS) region. The VIS pulse had a maximum energy of 180 mJ, a width of 4 ns, and was generated by a Quantel Brilliant Q-Switched Nd:YAG laser coupled to a second harmonic generator module. An ARYELLE 400-Butterfly system was used to detect and select the wavelengths. The spectrometer was operated in the spectral range 175–330 nm, with resolution of 13–24 pm, and was equipped with an intensified charge-coupled device (ICCD) camera ( $1024 \times 1024$  pixels). The beam from the lasers was directed and focused on the sample by means of dichroic mirrors at appropriate wavelength. Two lenses were placed between the sample and the tip of the fiber, for efficient collection of the emitted plasma. The sample support was placed in a micro-controlled x-y stage to enable easy and fast scanning by the laser beam impinging on it. An eight-channel pulse generator (Model 9618, Quantum Composers) was used to synchronize the delay time between pulse and the detection acquisition during the experiments.

Acquisition of the LIBS spectra was performed using a 532 nm visible laser beam with energy of 30 mJ and accumulation of 5 laser shots. The beam was focused and aligned to hit the sample in overlapping laser shots mode. The gate width was set at 1.5  $\mu\text{s}$  and the gate time at 1.0  $\mu\text{s}$ . Each whole soil and humic fraction sample was submitted to 30 measurements performed in different positions.

The outlier spectra were excluded using a technique called Spectral Angle Mapper (SAM) [20], involving calculation of a normalized scalar product between the individual spectrum and the average spectrum, returning a value between  $-1$  and  $1$ . The closer the value is to  $1$ , the greater the similarity between the spectra. The imposition of a limit below  $1$  enables the exclusion of spectra that differ from the average. The use of this procedure resulted in elimination of only around 2% of the spectra, indicative of good stability of the experimental system. Finally, an average spectrum was calculated for each sample.

### 2.6. Transitions identification

Identification of the Fe and Al transitions was performed using pixel correlation [11] and the NIST database [21]. Briefly, calculation was made of the linear Pearson correlation between the intensity of a specific pixel and the variation of the concentration. This process was repeated for all pixels in the spectrum. The reference elemental concentration value was measured by FAAS. In this way, the pixels with higher correlation values were more likely to be representative of a transition line. This analysis assisted in eliminating saturated transitions and those with interference. As a result, three transition lines were selected for each metal: Al I (237.20 nm), Al II (265.25 nm), Al (281.62 nm), Fe I (248.33 nm), Fe II (273.95 nm), and Fe (302.05 and 302.06 nm). The last Fe transition is a superposition of two Fe lines, so the integrated area of the entire region was used as a single intensity value.

### 2.7. Multivariate calibration

The LIBS intensity was linearly correlated with the Al and Fe concentrations of the samples, resulting in a calibration curve. The LIBS intensity was obtained by means of a multivariate calculation involving the areas for each transition and the area for the background, as shown in Eq. (1):

$$I = \alpha_1 * A_1 + \alpha_2 * A_2 + \alpha_3 * A_3 - \beta * C \quad (1)$$

where  $A_i$  is the area of each atomic transition,  $C$  is the background area, and  $\alpha_i$  and  $\beta$  are positive parameters fitted to the best linear correlation. The  $A_i$  values were calculated by summing the intensities of pixels inside a transition. The value of  $C$  was obtained as the sum of the intensities in a region with no apparent transitions.

## 3. Results and discussion

### 3.1. Metal and carbon concentrations at the humic fractions and whole soils

Table 1 shows the values for Fe and Al in the whole soil samples and in the humic fractions extracted from the Amazonian Spodosols, obtained using FAAS.

The Al concentration profile showed an increase with greater depth in the horizons of soils P1 and P4 (Table 1). In the case of Fe, the highest values were found for the subsurface horizons (A and A-E) and the deep Bh horizons: Bh-C 240 (P1) and Bh 370–380 (P4). A possible explanation for this behavior was that in the case of the hydromorphic Spodosol (P1), there was mobilization of suspended organometallic complexes and metal oxides, controlled by the oscillating groundwater level. In flooded soils, anaerobic environments are created, with the organic matter acting as an electron receptor and enabling reduction of the macro- and micronutrients present [23,24]. Hence, the results suggested that there was greater mobilization of the organometallic complexes and the reduced iron in soil P1, compared to the well-drained Spodosol (P4), with the precipitation of Fe and decreasing mobilization of the organometallic complexes along the profile. Consequently, there was the accumulation of Fe in horizons with greater amounts of organic matter, resulting in spodic Bh horizons in this system.

The results obtained in this study were in agreement with the findings of Ishida [25] and Santos [22] for a Latosol-Spodosol system in the Amazon region. It was reported that there was accumulation of Al and Fe in the Bh horizons, with the highest value obtained for Al. This accumulation was suggested to be due to translocation of the metals, especially Al, to the spodic Bh horizons in the form of organic complexes.

Fig. 2 shows the carbon concentration (%) for the whole soil and humic fractions from different depth for P1 and P4 soils.

The results show that high concentration of carbon present in the

**Table 1**

Concentrations of metals Fe and Al (g/kg) by FAAS in the whole soil samples and in the humic fractions (HA, FA, and HU) extracted from the Amazonian Spodosols.

Metals	Samples			Concentration of metals (g/kg)			
	Area	Horizon	Depth (cm)	Soils	HA	FA	HU
Fe	P1	A	0–15	1.20 ± 0.01	0.4 ± 0.2	0.07 ± 0.01	0.3 ± 0.1
		A-E	15–30	0.95 ± 0.01	0.3 ± 0.1	*	0.2 ± 0.1
		Bh	40–50	0.77 ± 0.01	0.3 ± 0.1	0.12 ± 0.01	0.2 ± 0.1
		Bh-C	240	6.44 ± 0.01	0.6 ± 0.2	*	0.4 ± 0.1
		C	350	2.13 ± 0.01	0.2 ± 0.1	0.07 ± 0.01	1.0 ± 0.2
	P4	A	0–20	2.29 ± 0.01	1.8 ± 0.5	0.2 ± 0.1	0.2 ± 0.1
		A	20–30	2.28 ± 0.01	1.9 ± 0.4	*	0.2 ± 0.1
		A	30–40	2.60 ± 0.01	2.3 ± 0.3	*	0.3 ± 0.1
		Bh	110–120	1.81 ± 0.01	1.1 ± 0.2	*	0.4 ± 0.1
		Bh	170–180	1.72 ± 0.01	1.4 ± 0.2	*	0.3 ± 0.1
		Bh	370–380	2.49 ± 0.01	1.2 ± 0.6	*	0.4 ± 0.1
		Bh	380–390	1.66 ± 0.01	1.3 ± 0.2	*	0.3 ± 0.1
Al	P1	A	0–15	43 ± 1	*	16.8 ± 0.2	*
		A-E	15–30	39 ± 1	*	13.8 ± 0.5	*
		Bh	40–50	57 ± 1	*	8.8 ± 0.3	*
		Bh-C	240	92 ± 1	*	*	*
		C	350	52 ± 1	*	20.0 ± 0.1	5.0 ± 0.1
	P4	A	0–20	48 ± 1	6.4 ± 0.4	9.5 ± 0.1	*
		A	20–30	47 ± 1	*	27.2 ± 0.2	*
		A	30–40	46 ± 1	*	17.5 ± 0.1	*
		Bh	110–120	39 ± 1	*	13.7 ± 0.4	*
		Bh	170–180	49 ± 1	*	16.5 ± 0.3	*
		Bh	370–380	41 ± 1	*	20.5 ± 0.2	*
		Bh	380–390	51 ± 1	*	21 ± 1	*

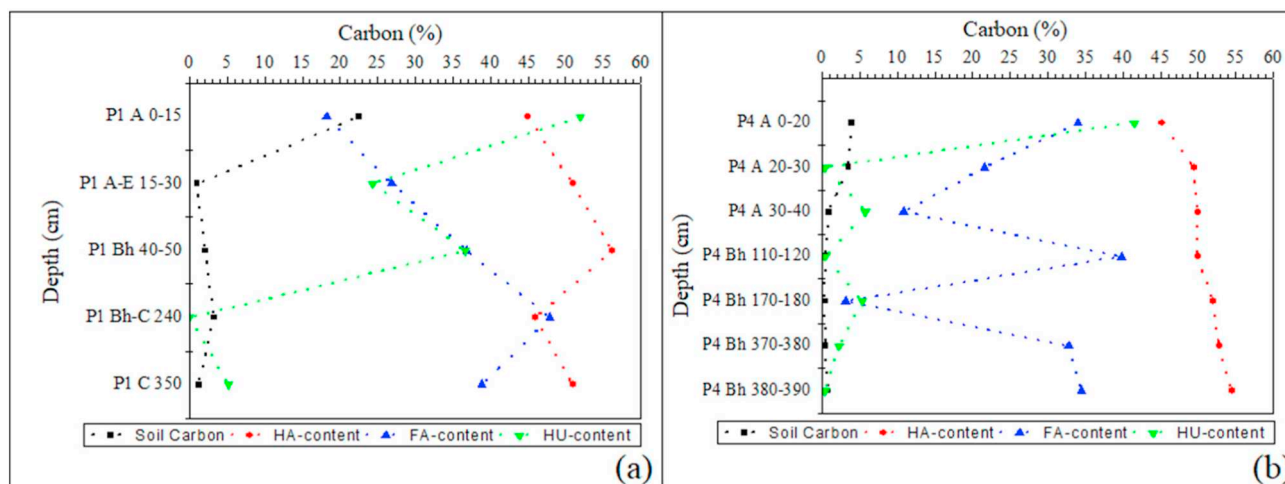
P1: hydromorphic spodosol; P4: well drained spodosol; \* below the detection limit of the calibration curve (Fe: 0.10 mg/kg and Al: 2.5 mg/kg).

(SOM) was observed in surface horizons of P1 and P4 soils, represented by the black dash: P1 A 0–15 and P4 A 0–20, respectively (Fig. 2(a) and (b)). Spodosol Amazon poorly drained (in this study, refers the P1), it can be have Bh horizons with 1 cm thick and to store unexpected amounts of carbon in these horizons [26]. There is a carbon accumulation in the deeper Bh horizons mainly for P1 soil, which can be associated to the incorporation of simpler structure with aliphatic chains and/or more unstable structures of the SOM, thus reflecting in a lower humification index [13].

The carbon values in the humic acid fractions (represented by the red dash, Fig. 2) obtained carbon values from 45 to 56.2%, corroborating with studies described in the literature [27–29]. Fig. 2(a) shows low carbon values of the humic acid fraction in the surface horizons by P1 A 0–15. In Fig. 2(b), there was little variation in the amount of carbon for the humic acid samples. Humic fraction values were higher

carbon in the surface horizons for P1 A 0–15 and P4 A 0–20 (Fig. 2(a) and (b)). In fulvic acid, there was little variation between carbon values along the depth at soil P1 (Fig. 2(a)), whereas in soil P4 (Fig. 2(b)) there was high variation with depth and an increase in the carbon value in the deeper horizons.

In previous study by Tadini et al. [13], involving the dating of these Amazonian Spodosols and determination of the humification indices, it was observed that soil P1 presented an accumulation of young organic material with a low degree of humification, which was displaced with depth, due to physical and chemical processes. The highest values for humification of the whole soil and for the humic acid fraction were obtained for the Bh-C horizon, at 240 cm (P1 Bh-C 240). The data obtained in the present study (Table 1) showed that this horizon presented the highest concentrations of Fe and Al in the whole soil and the humic fractions (HA, FA, and HU).



**Fig. 2.** Carbon concentration (%) for the Amazonian Spodosols by P1 (a) and P4 (b) soils. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The well-drained Spodosol (soil P4) showed the contribution of old and poorly humified organic matter in horizons Bh 170–180 and Bh 370–380. Therefore, the results indicated that the transfer of iron and aluminum to deeper profiles of soil P1 involved the participation of young and less humified organic matter. Transfer of the metals in soil P4 involved older organic matter with a low degree of humification, which could be attributed to the presence of more recalcitrant compounds derived from lignin [13].

These results indicated that the three humic fractions were involved in the process of podzolization of the Amazonian Spodosols. The FA fraction played a predominant role in the transport of Al (8.8 to 27.2 g/kg), since this fraction had the highest amount of this metal in its structure, while the HA fraction was responsible for the transport of Fe (0.2 to 2.3 g/kg).

### 3.2. Relationships between spectroscopy analysis and metals

The LIBS technique was also used for analysis of the whole soil samples and the humic fractions extracted from the Amazonian Spodosols. Fig. 3 show typical LIBS spectra obtained for horizon A of the hydromorphic Spodosol (P1).

After obtaining the LIBS spectra, the data for specific lines were treated in order to determine the concentrations of Fe and Al present in the whole soil and in the humic fractions. The lines selected were as follows: 248.32708 nm (Fe I), 273.95474 nm (Fe II), 302.04907 nm (Fe

II), 265.2484 nm (Al I), 281.6185 nm (Al II), and 237.2070 nm (Al I). Three transitions were used for each metal, together with the background. A simple multivariate background analysis was used to obtain the LIBS intensity and correlate it with the concentration of Fe or Al.

Fig. 4 shows the graphs for the correlations between the LIBS intensities and the Fe concentrations (g/kg) obtained by FAAS analysis of the whole soil samples and the humic fractions. Very strong Pearson correlations were obtained for the humic acid and humin fractions, with R values of 0.95 and 0.97, respectively (Fig. 4(a) and (b)), while weaker correlations were found for the whole soils and the fulvic acid fractions. This suggested that the former two fractions, especially the humic acids, strongly participated in the transport of Fe to other horizons of the Amazonian Spodosols.

Fig. 5 shows the correlation graphs for the LIBS intensity and [Al] (g/kg) determined by FAAS, for the whole soil samples and the fulvic acid fractions. Strong Pearson correlations were obtained for both the whole soil ( $R = 0.90$ ) (Fig. 5(a)) and the fulvic acid fraction ( $R = 0.97$ ) (Fig. 5(b)), indicating that the simplest fraction of the organic matter of these Amazonian Spodosols (the fulvic acids) was most important for the transport of Al. The results shown in Figs. 4 and 5 were in agreement with those presented in Fig. 3. Consequently, in the case of the hydromorphic Spodosol (P1), the presence of groundwater outcrops favored the movement of this metal towards the deeper horizons, as observed by the high amounts of this metal in the whole soil (Table 1), compared to the well-drained Spodosol (P4).

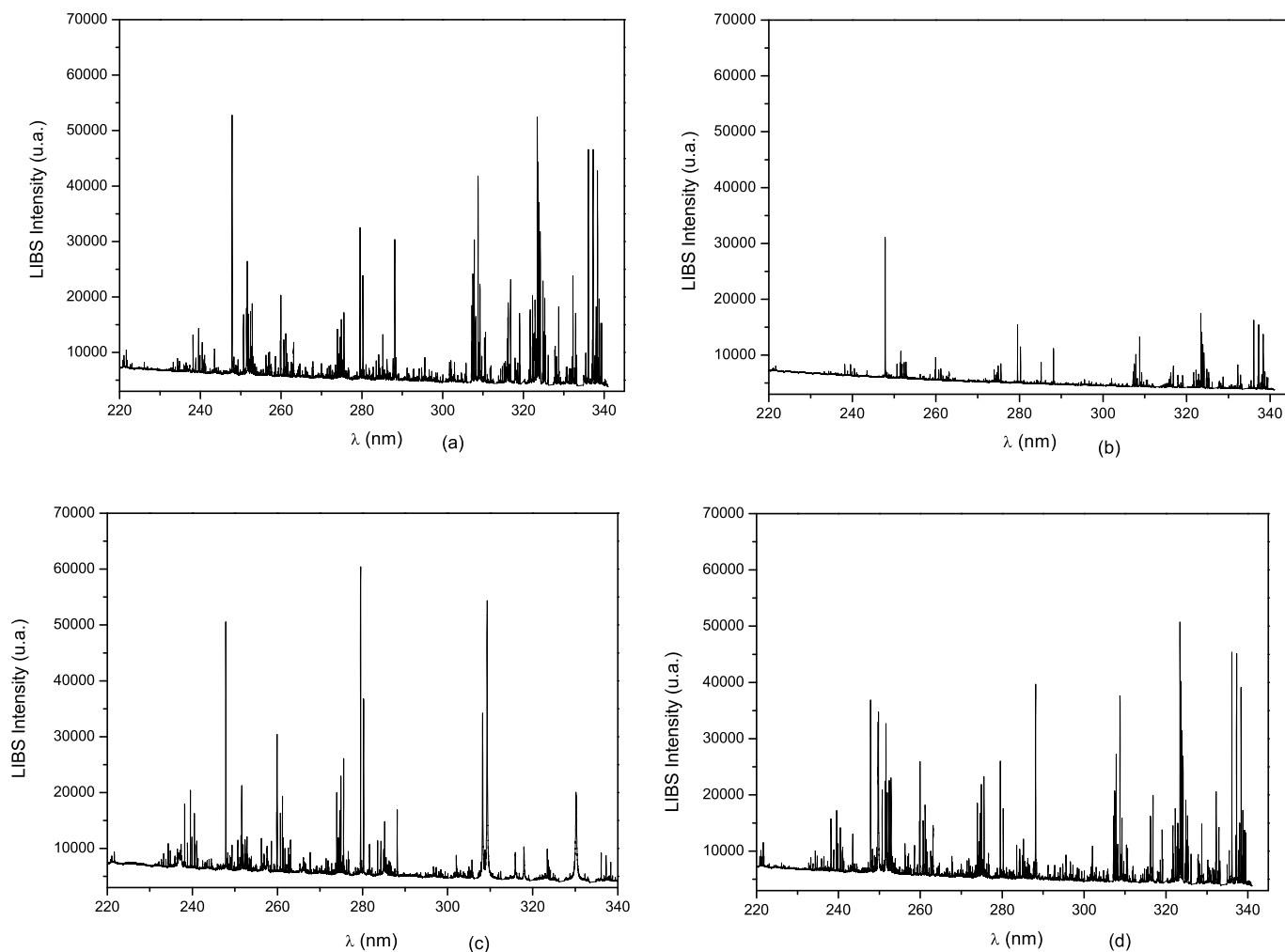


Fig. 3. Typical LIBS spectra for the hydromorphic spodosol (P1 A 0–15 cm): (a) whole soil, (b) humic acids, (c) fulvic acids, and (d) humin.



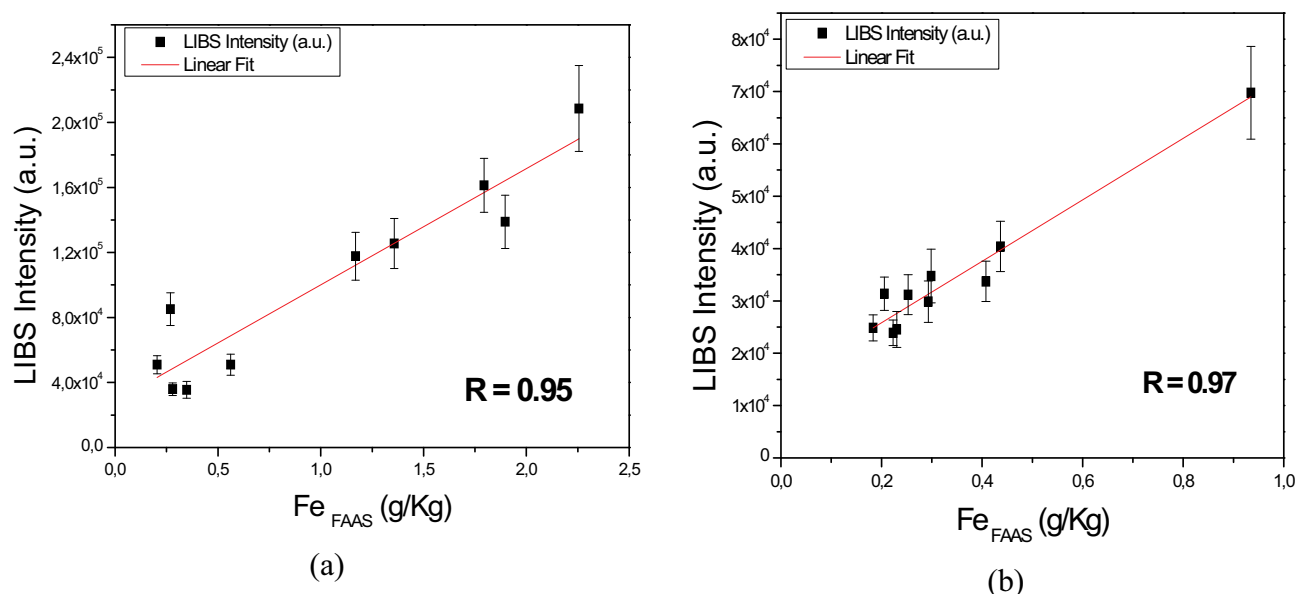


Fig. 4. Correlations between the LIBS intensities and the Fe (g/kg) concentrations by FAAS in the Amazonian Spodosol samples: (a) humic acids; (b) humin.

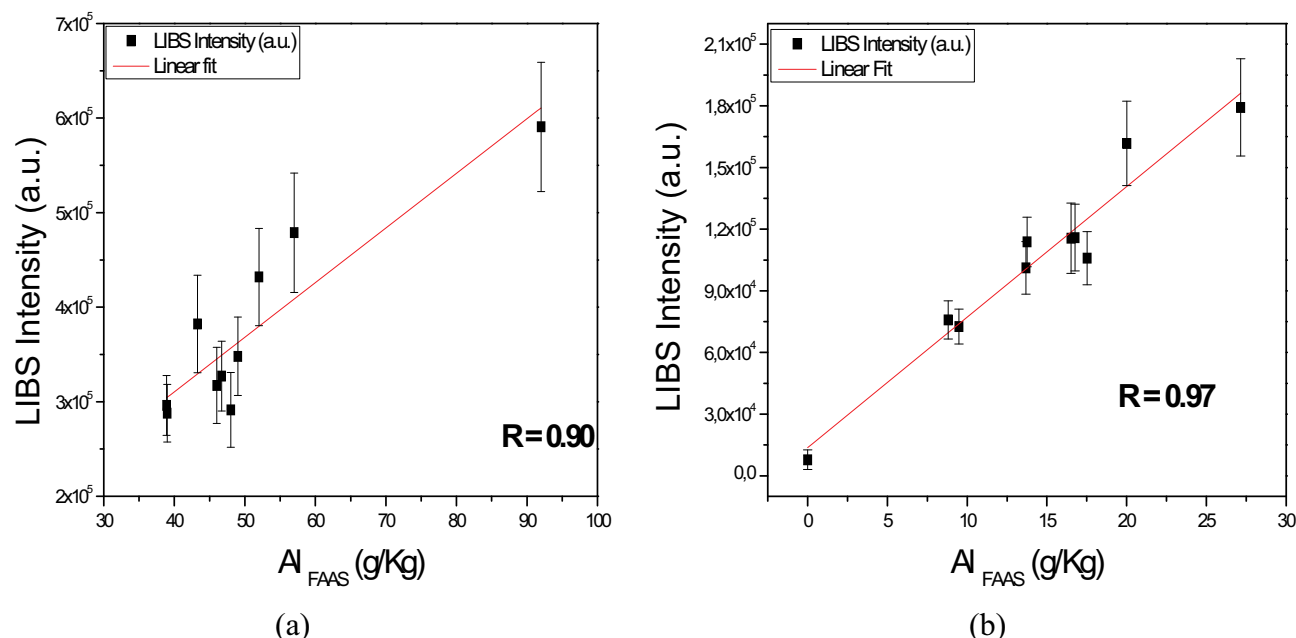


Fig. 5. Correlations between the LIBS intensities and the Al (g/kg) concentrations by FAAS in the Amazonian Spodosol samples: (a) whole soil; (b) fulvic acids.

#### 4. Conclusions

The results showed that the fulvic acid fraction were associated with high amounts of Al in the soils, while the humic acid fraction was more selective towards Fe. The transfer of Fe and Al to deeper profiles involved young and less humified organic matter (soil P1), or older organic matter with a low degree of humification (soil P4). It could therefore be concluded that the three humic fractions (HA, FA, and HU) were involved in the soil podzolization process, with the FA and HA fractions playing predominant roles in the transport of Al and Fe, respectively.

The efficiency of the LIBS technique for analysis of the processes of formation of Amazonian Spodosols was also evaluated. The data obtained showed strong correlations with the results of analyses using the reference method (FAAS), for Fe in the humic acid and humin fractions

( $R = 0.95$  and  $0.97$ , respectively), and for Al in the fulvic acid fraction ( $R = 0.97$ ). This is the first study using LIBS applied to samples of environmental humic fractions. In combination with FAAS, it enabled understanding of the roles of the humic fractions in the transport of nutrients and in the process of formation of Amazonian Spodosols.

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